# Ocean Variability Effects on Underwater Acoustic Communications

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## LONG-TERM GOALS

This proposed research seeks to identify, explain, and ultimately predict, the factors that significantly alter the operational effectiveness of underwater acoustic communications through experimental work and theoretical analysis. The long-term goal is to develop reliable, high rate transceivers customized for coherent underwater acoustic communications.

## OBJECTIVES

The research objective is to investigate the relationship between environmental fluctuations and the performance of coherent underwater acoustic communications at high frequencies (8-50 kHz) through experimental research and data analysis. High rate communication methods are to be developed based on the understanding of acoustic propagation physics in dynamic shallow water enviroments.

## APPROACH

High rate acoustic communications in the ocean is a challenging task in the presence of environmental variability. There exist two kinds of variability: 1) rapid fluctuations of the channel over scales of seconds due to small-scale fast ocean processes, dynamic ocean surfaces, and possibly source/receiver motion and 2) long-term channel variations over scales of hours resulting from large scale oceanographic processes. The rapid channel fluctuations have been dealt with by various adaptive receiver structures developed since the 1990s. For example, multichannel adaptive equalizers track the channel either implicitly through the equalizer coefficients or explicitly as in channel-estimate-based decision feedback equalizers (CE-DFE) [1-2]. Recently, adaptive time reversal approaches have been proposed to accommodate either fast time-varying channels or long-duration data packets [3-4].

| **Report Documentation Page** | | *Form Approved*<br>*OMB No. 0704-0188* |
|---|---|---|



| | | |
|---|---|---|
| 1. REPORT DATE<br>**2009** | 2. REPORT TYPE | 3. DATES COVERED<br>**00-00-2009 to 00-00-2009** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Ocean Variability Effects On Underwater Acoustic Communications** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**University of Delaware,College of Marine and Earth Studies,114C Robinson Hall,Wilmington,DE,19806** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT

**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

**This proposed research seeks to identify, explain, and ultimately predict, the factors that significantly alter the operational effectiveness of underwater acoustic communications through experimental work and theoretical analysis. The long-term goal is to develop reliable, high rate transceivers customized for coherent underwater acoustic communications.**

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **7** | |

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Prescribed by ANSI Std Z39-18

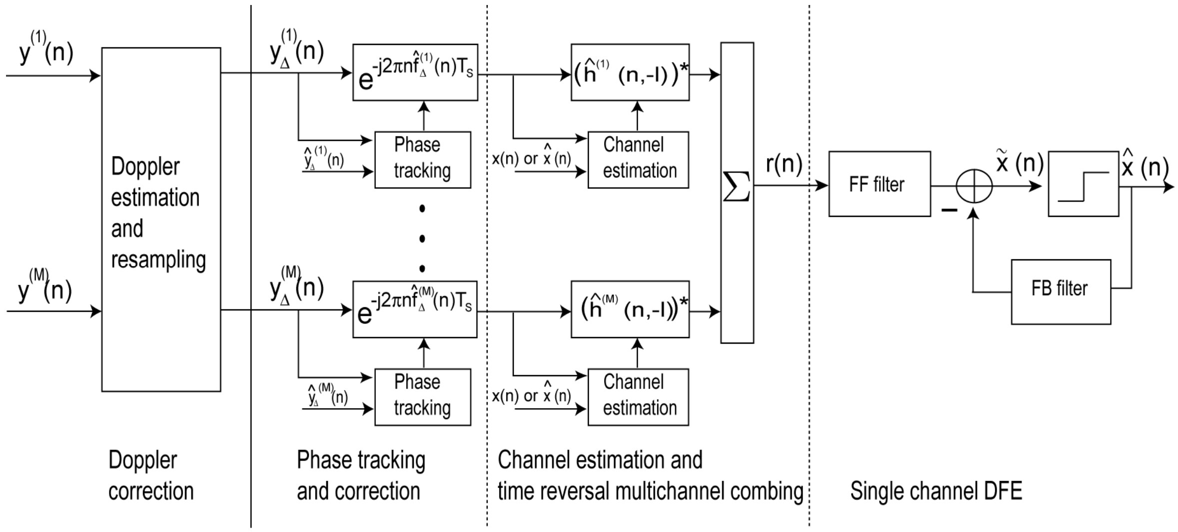


***Fig. 1. Time reversal receiver for high rate acoustic communications. The receiver consists of four components: (1) Doppler correction through the use of time domain re-sampling, (2) phase tracking and correction at individual channels, (3) multichannel time reversal combining aided by frequent channel updates, (4) single channel DFE.***

Much of the research to date has focused on short-term communications for a given ocean environment in order to develop an efficient, reliable receiver structure and to improve communications performance. Although it is equally important to understand how long-term ocean variability affects communications performance, there have been few studies reported in the literature because they involve an extended period of acoustic transmissions and concurrent environmental measurements. During the past few years, we have participated in a series of high frequency acoustic communication experiments, i.e., KauaiEx [5], MakaiEx [6], and KAM08 [7], in which extended acoustic measurements and concurrent environmental monitoring have been performed.

The time reversal receiver we developed in Ref. [3] is employed to process the communications data. The receiver consists of four components: (1) Doppler correction through the use of time domain re-sampling, (2) phase tracking and correction at individual channels, (3) multichannel time reversal combining aided by frequent channel updates, (4) single channel DFE. The core idea is to update the individual channel estimates prior to time reversal multichannel combining using previously detected symbols, followed by a single channel DFE for near-optimal performance. The output signal-to-noise ratio (SNR) of the soft DFE output is used as the performance metric.

## WORK COMPLETED

*Data analysis of the KAM08 experiment.* The Kauai Acoustic communications MURI (KAM08) experiment was conducted west of Kauai, Hawaii, during summer 2008. As illustrated in Fig. 2, high frequency sequences (10-20 kHz) were transmitted every 30 min over 35 hours from a wide aperture 8-element source array to a 16-element vertical receiving array at 4 km range covering a significant portion of the water column. During the acoustic transmissions, the water temperature structure and sea surface conditions were monitored by the thermistor string and directional waverider. A distinguished feature of the ocean environment at the KAM08 site is its thermocline variability. As shown in Fig.

3(a), for most of the time the water column was well mixed down to about 50 m depth. A cold layer (about 4-5 degree) lower than the mixed layer) emerged at nearly tidal cycles. The objective of the current effort is to study the effects of the source/receiver geometry in conjunction with the water column variability on shallow-water communications performance, as continuing investigations presented in [3]. It is shown that source depth has significant impact on receiver performance in the presence of water column variability.

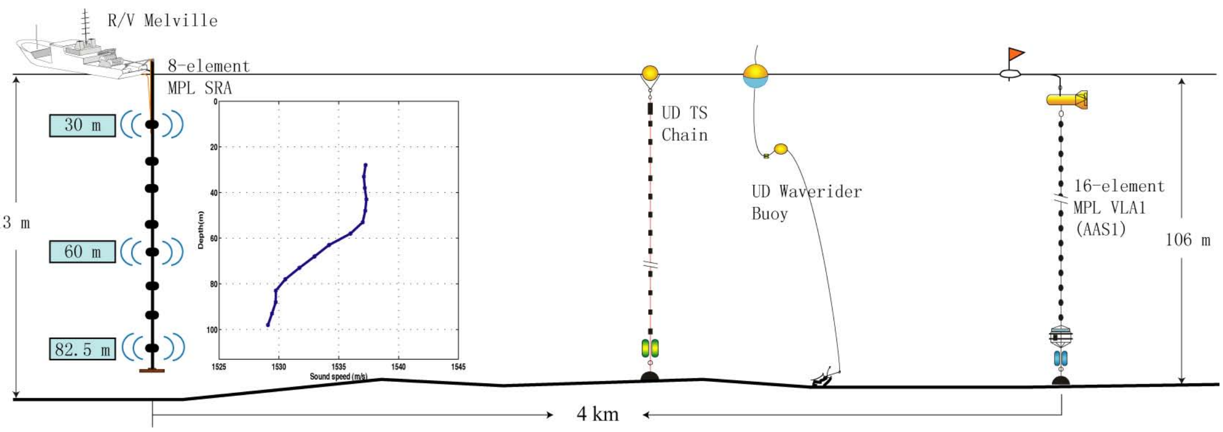


***Fig. 2. Experimental setting during KAM08. A representative sound speed profile also is shown.***

## RESULTS

In order to show the effects of the source/receiver geometry in conjunction with the water column variability on acoustic communication performance, we chose representative source and receiving subarrays with respect to the thermocline, which significantly influences acoustic propagation in shallow water. Specifically, three sources at depths of 30 m (top), 60 m (middle), and 82.5 m (bottom) are selected from the source array corresponding to the upper, middle and lower water column, respectively. For the VLA, two sets of subarrays are considered: (1) bottom six elements denoted as the bottom subarray and (2) top six elements denoted as the  top subarray. The source/receiver locations are marked in Fig. 3(a). We can envision the thermocline positioned roughly between the warm (red) and cold water (blue) in Fig. 3(a). Note that the 30-m and 82.5-m sources are mostly above and below the thermocline, respectively, while the 60 m source is in and out of the thermocline during the experiment. Extending from 76 to 95 m, the  bottom subarray is mostly below the thermocline. The top subarrray covers the water column from 42 to 61 m so that a few of the deeper elements can fall in or below the  thermocline. It should be mentioned that the six elements in either subarray provide reasonable performance for all three source depths.

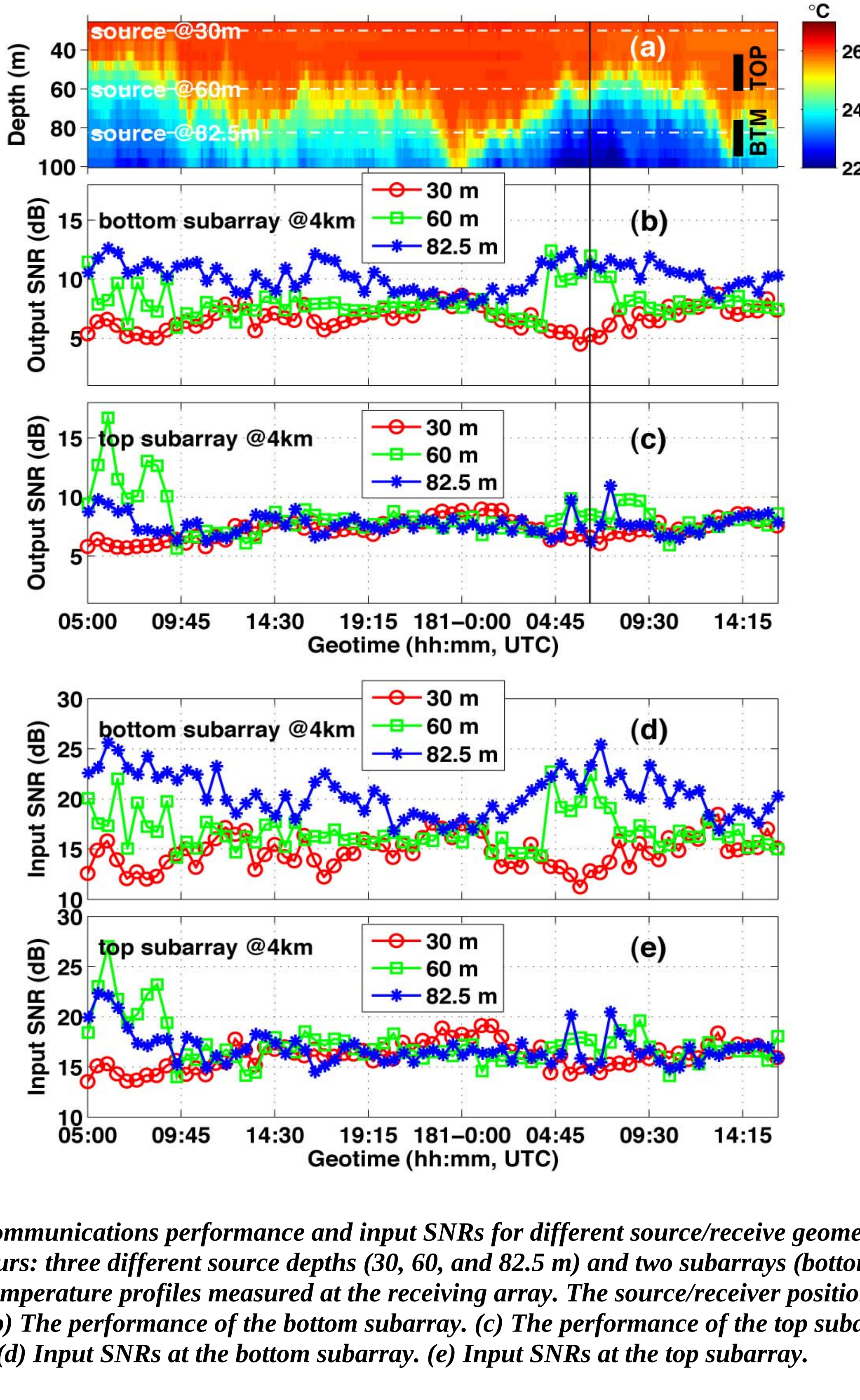


***Fig. 3. Communications performance and input SNRs for different source/receive geometries over 35 hours: three different source depths (30, 60, and 82.5 m) and two subarrays (bottom and top). (a) Temperature profiles measured at the receiving array. The source/receiver positions are marked. (b) The performance of the bottom subarray. (c) The performance of the top subarray. (d) Input SNRs at the bottom subarray. (e) Input SNRs at the top subarray.***

***Bottom subarray***

The communications performance using the bottom 6-element subarray is shown in Fig. 3(b) for three different source depths: 30, 60, and 82.5 m. A few interesting observations can be made. First, it is evident that the bottom source (*) consistently outperforms the top source (○). A thermocline in shallow water results in a downward-refracting environment where acoustic energy is trapped below the thermocline. \cite{Jensen-Acoustics} In this case, the thermocline acts like an acoustic barrier (or wall) so that it is difficult to transfer energy across the barrier when a source and a receiver are on the opposite sides of the barrier. Note that as indicated in Fig. 3(a) with a vertical bar, the bottom subarray is mostly located below the thermocline. Consequently, the bottom source which is well below the thermocline has much better performance (6-7 dB) than the top source which is above the thermocline.

Second, the middle source (□) experiences a large variation in performance (i.e., 6-7 dB) depending on whether it is in or out of the thermocline. In fact, the middle source acts like the bottom source (*) when it is below the thermocline and like the top source (○) when it is above. Thus the performance of the middle source is bounded above by the bottom source (*) and below by the top source (○), resulting in the significant variation observed over the analysis period.

Third, when a source is in the middle of the thermocline, it is interesting to note that the performance is strongly affected by the thermocline gradient. Consider two geotimes 3 h apart on JD181, 06:30 (vertical line) and 09:30. Clearly, the performance at 6:30 is superior to that at 9:30 by as much as 4-5 dB as shown in Fig. 3(b). While the thermocline acts like an acoustic barrier, a steeper gradient at 6:30 makes the barrier tighter such that the effective water depth is bounded by the top of the thermocline. On the other hand, some of the energy leaks into the water column above the thermocline when the gradient is weaker as at 9:30.

Lastly, around JD181 00:00 all three source depths exhibit similar performance in Fig. 3(b). The corresponding temperature profile in Fig. 3(a) indicates that the water-column is well-mixed down to 100-m deep, resulting in an almost homogeneous (iso-speed) waveguide (no thermocline). In this case, there is no performance difference between the bottom and top sources.

***Top subarray***

Using the top 6-element subarray, the performance is shown in Fig. 3(c) for the three different source depths. Unlike the bottom subarray in Fig. 3(b), the performance is relatively flat, except for two periods which will be discussed in the following paragraph. Since a portion of the top subarray itself is in and out of the thermocline, it is not quite as clear-cut to illustrate the impact of the source/receiver geometry. Nonetheless, a mode theory perspective provides some insight as follows [8]. The top source (*) usually excites many, but weak high-order modes, whereas the bottom source (□) excites fewer, but stronger low-order modes. The overall contribution of the energy picked up by the top subarray appears comparable for these two sources. In fact, this argument is well supported by the input SNR displayed in Fig. 3(e) which resembles Fig. 3(c). The input SNR is calculated at the output of time reversal combining based on the channel estimates and measured noise intensity. Further, we also note the remarkable similarity between Figs. 3(b) and (d) for the bottom subarray.

Notable exceptions from the performance being flat can be found during two periods: 05:00-09:30 for both JD180 and JD181. During this time, the middle (□) and bottom (*) sources fall below the thermocline along with 3-4 bottom elements of the top subarray, resulting in both the source and some receiving elements being on the same side of the thermocline. Consequently, these two source locations yield better performance than the top source (○) which is above the thermocline. What is interesting here is that the middle source (□) outperforms the bottom source (*), as opposed to the case shown in Fig. 3(b) for the bottom subarray. This is due to the fact that the middle source can ensonify the upper water column more effectively than the bottom source. Again, this is confirmed in Fig. 3(e) where the input SNR closely follows the performance in terms of output SNR.

***Summary***

It was shown that the source in the middle of the water column (60 m) which was either in or out of the thermocline experiences performance variability of as much as 6-7 dB in terms of output SNR. Moreover, the source below the thermocline (82.5 m) consistently outperformed the source above the thermocline (30 m) when the receiver is located below the thermocline. It was also confirmed that the communications performance (output SNR) closely follows the characteristics of the input SNR associated with the acoustic energy ensonifying a given subset of receiving array elements.

## IMPACT/APPLICATIONS

The developed receiver is a low-complexity structure for robust, high data rate underwater digital communications at high frequencies. It can drastically improve data rates of underwater acoustic modems. The relationship between ocean environment fluctuations and acoustic modem performance can guide future modeling efforts.

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